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Economic analysis of power generation from parabolic trough solar thermal plants for the Mediterranean region—A case study for the island of Cyprus

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ABSTRACT

In this work a feasibility study is carried out in order to investigate whether the installation of a parabolic trough solar thermal technology for power generation in the Mediterranean region is economically feasible. The case study takes into account the available solar potential for Cyprus, as well as all available data concerning current renewable energy sources policy of the Cyprus Government, including the relevant feed-in tariff. In order to identify the least cost feasible option for the installation of the parabolic trough solar thermal plant a parametric cost–benefit analysis is carried out by varying parameters, such as, parabolic trough solar thermal plant capacity, parabolic trough solar thermal capital investment, operating hours, carbon dioxide emission trading system price, etc. For all above cases the electricity unit cost or benefit before tax, as well as after tax cash flow, net present value, internal rate of return and payback period are calculated. The results indicate that under certain conditions such projects can be profitable.

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1. Introduction

Solar thermal power generation utilizes the sun as a source of heat which can be exploited by concentrating that heat and using it to drive a heat engine to produce power. As such, solar thermal power generation is much more closely related to traditional forms of power generation based on fossil fuel combustion which also rely on heat engines to convert heat into electrical energy.

Solar thermal generation is not new. The first patent for a solar collector was granted in Germany in 1907. However, the first major effort to exploit the sun as a heat source for power generation began in the US after the oil crises of the 1970s and the first commercial plants appeared in the late 1980s in California. Funding for development and deployment of solar thermal generation tailed off soon afterwards when cheap natural gas dominated the power generation market in most parts of the developed world. However, the combination of global warming and volatile gas prices has had a potent effect and both interest and investment in solar thermal power technology are now accelerating rapidly.

Investment is what solar thermal power technology has lacked for most of the past 20 years. With sufficient investment there is no doubt that solar thermal electricity generation can provide an economical source of electricity. The conditions now seem right for it to prosper. With several major projects proposed, under construction or recently entering service there is finally a strong chance that this electricity generating technology can become a part of the main stream, alongside wind, hydro and solar photovoltaic technologies, as a key source of renewable energy for the future.

The purpose of this work is to investigate whether the installation of a parabolic trough solar thermal technology for power generation in the Mediterranean region is economically feasible. The case study takes into account the available solar potential for Cyprus, as well as all available data concerning current renewable energy sources policy of the Cyprus Government, including the upcoming relevant feed-in tariff of 0.26 €/kWh. In order to identify the least cost feasible option for the installation of the parabolic trough solar thermal plant a parametric cost–benefit analysis is carried out by varying the following parameters: (a) parabolic trough solar thermal plant capacity 25 MW or 50 MW or 100 MW, (b) parabolic trough solar thermal capital investment from 2000 €/kW to 8000 €/kW, (c) operating hours from 5 h/day to 24 h/day, (d) required land leasing from 0 €/m^2 to 3 €/m^2 and (e) CO_2 emissions trading scheme (ETS) price 0 €/t_{CO2} or 30 €/t_{CO2}. For all above cases the electricity unit cost or benefit before tax (in €/kWh), as well as after tax cash flow, net present value (NPV), internal rate of return (IRR) and payback period are calculated.

In Section 2, the available solar thermal power technologies are resented and in Section 3, the solar thermal power plants in operation around the world are discussed. A description of Cyprus current energy system is presented in Section 4. In Section 5, the parametric cost–benefit analysis is carried out and the results are discussed in detail. The conclusions are summarized in Section 6.

2. Available solar thermal power technologies

Solar energy is the energy force that sustains life on earth for all plants, animals and people. The earth receives this energy from the sun in the form of electromagnetic waves, which the sun continually emits into space. The earth can be seen as a huge solar energy collector receiving large quantities of this energy which takes various forms, such as direct sunlight, heated air masses causing wind, and evaporation of the oceans resulting as rain which can form rivers. This solar potential can be trapped directly as solar energy and indirectly as wind, biomass and hydroelectric energy.

Solar energy is a renewable source that is inexhaustible and is locally available. It is a clean energy source that allows for local energy independence. The sun's power that is reaching the earth annually is typically about 1000 W/m^2, although availability varies with location and time of year. Capturing solar energy typically requires equipment with a relatively high initial capital cost. However, in some cases, over the lifetime of the solar equipment, these systems can prove to be cost competitive, as compared to conventional energy technologies.

The solar energy industry is divided into mainly two markets, the photovoltaic (PV) market and the solar thermal market. The solar thermal technology uses the heat radiated from the sun, for purposes such as heating water or power generation. On the other hand PV solar cells use the properties of particular semiconducting materials to convert sunlight energy to electricity.

Current solar thermal power technologies are distinguished in the way they concentrate solar radiation, such as, (a) parabolic trough systems, (b) solar tower systems and (c) solar dish systems. The direct radiation is concentrated using reflectors and the energy concentrated in this way is transformed into steam, which is used to drive conventional electricity generators [5]. A brief description of each most common available solar thermal power technology and of thermal storage is provided below.

2.1. Parabolic trough technology

A parabolic trough is a long, trough-shaped reflector with a parabolic cross-section as indicated in Fig. 1 [13]. As a result of this

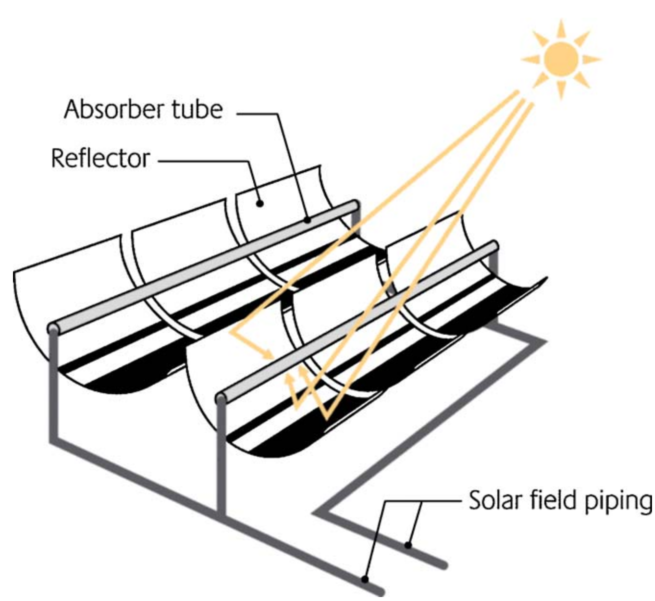

Fig. 1. Principle of operation of parabolic trough system [13].

cross-section, sunlight reflected within the trough is focused along a line running the length of the trough. In order to collect this heat, a pipe is positioned along the length of the trough at its focus and a heat collection fluid is pumped through it. The tube (or receiver) is designed to be able to absorb most of the energy focused onto it and must be able to withstand the resultant high temperature. Typical receivers for this purpose are made of steel tubing with a black coating and surrounded by a protective glass cover with the space between the two evacuated to reduce heat loss. An anti-reflective coating may be added to the outer glass surface to increase efficiency further.

The solar array of a parabolic trough power plant consists of several parallel rows of parabolic reflectors. The heat collecting fluid which is pumped through the pipes along the length of each solar trough is typically synthetic oil, similar to engine oil, capable of operating at high temperature. During operation it is likely to reach between 300 °C and 400 °C. After circulating through the receivers the oil is passed through a heat exchanger where the heat it contains is extracted to raise steam in a separate sealed system and the steam is then used to drive a steam turbine generator to produce electricity. The heat collecting fluid is then cycled back through the solar collector field to collect more heat.

The parabolic troughs along which these tubular receivers run may be 5–6 m wide, 1 m or 2 m deep and up to 150 m in length (though an individual trough of this length will usually be constructed from modular sections). Many of these are required to collect sufficient energy to provide heat for a single power plant. As a consequence, these solar troughs form a physically large part of the solar plant and their cost can have a significant impact on plant economics.

Parabolic solar troughs are usually aligned with their long axes from north to south and they are mounted on supports that allow them to track the sun from east to west across the sky. These supports may be made of steel or aluminum. In the first commercial plants the actual mirrors were made from 4 mm glass which is both heavy and expensive. Modern developments aim to reduce the cost and weight by using new techniques and materials including polished aluminum instead of coated glass mirrors. Energy conversion efficiency is one of the keys to commercial success for solar thermal plants. The reflecting mirrors must be both accurately shaped, and accurately positioned in order to achieve maximum solar collection efficiency. Then the tracking system must ensure that each trough is in the optimum position, all day. Finally the tubular energy receivers must operate at the highest efficiency possible too.

2.1.1. Parabolic trough with direct steam generation

The heat collection system currently employed in parabolic trough plants involves use of synthetic oil as the heat collection fluid and, as outlined above, this must be passed through a heat exchanger in order to raise steam to drive a turbine. An obvious simplification to this system can be achieved by replacing the heat collection fluid with water. If water is used, it can be converted directly to steam within the heat collection pipes of the collector field and then used immediately to drive the plant's steam turbine without the need for heat exchangers. This could result in a significant reduction in plant costs but technical requirements are more demanding.

2.1.2. Hybrid parabolic trough—fossil fuel power plants

With solar radiation only available for part of each 24 h, energy storage, as discussed above, represents one means of providing power around the clock. An alternative way of exploiting solar energy when continuous power is needed is to combine a solar thermal power plant with a fossil fuel power plant. Solar heat, when available, can then be used to supplement the heat available from combustion of fossil fuel, reducing carbon dioxide emissions and increasing the renewable contribution to gross power generation.

The most promising hybrid arrangement under consideration involves building a solar thermal power plant based on parabolic troughs alongside a combined cycle power plant, an arrangement called an integrated solar combined cycle (ISCC) plant. In an ISCC plant the combined cycle plant is built in a standard configuration with a gas turbine burning natural gas to generate electricity while the exhaust heat from the turbine is fed into a waste heat boiler, generating steam to drive a steam generator. In the hybrid plant, however, the heat from the solar collectors is used to supplement the heat from the gas turbine exhaust, increasing the output from the steam turbine section of the plant. Currently such plants are under construction in Morocco, Algeria and Egypt [11].

2.2. Solar towers

Solar towers (often called solar central receiver power plants) offer an alternative method of exploiting the energy from the sun in a solar thermal power plant. In this case the collector field consists of an array of heliostats (mirrors) at the centre of which is a tower as illustrated in Fig. 2 [13]. At the top of the tower is a receiver designed to collect the heat from the sun.

In operation each heliostat has an individual tracking system and all are aligned so that the sunlight striking them is directed onto the receiver which is located at the top of the central tower [1]. As the sun moves across the sky, each mirror must be moved too if high collection efficiency is to be maintained. The receiver itself is designed to absorb the energy from the sunlight incident upon it and transfer it to a heat transfer fluid. Depending on system design, this heat transfer may be either, water, a molten salt or air. Solar towers are normally designed with energy storage capability so that they can, in principle, operate 24 h a day [2].

2.3. Solar dishes

A solar dish power plant uses a circular parabolic dish to collect solar radiation and bring it to a focus, as illustrated in Fig. 3 [13]. A heat engine situated at the focus exploits the heat generated by this concentration to provide mechanical motion which drives a generator. In the case of the solar dish, the heat engine is normally a special type of engine called a Stirling engine which has extremely high efficiency. There have also been attempts to use

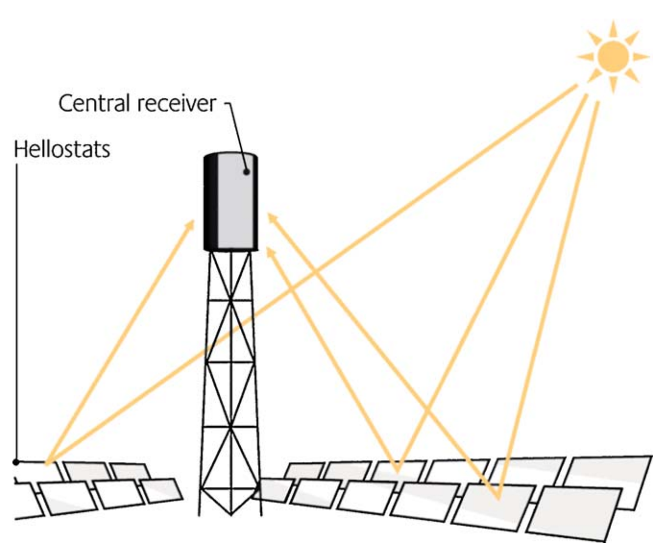

Fig. 2. Principle of operation of solar tower system [13].

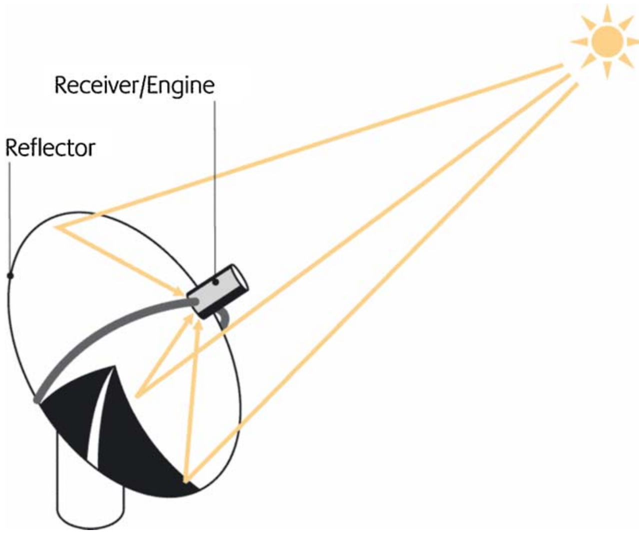

Fig. 3. Principle of operation of solar dish system [13].

small gas turbines based on the Brayton cycle (the thermodynamic cycle upon which the gas turbine is based).

Typical dishes are between 5 m and 10 m in diameter and with reflective areas of 40–120 m^2 though they have been built as large as 400 m^2. Material limitations are likely to restrict the practical size of dishes though dishes up to 15 m in diameter (700 m^2) have been proposed. Dishes in this size range could provide up to 50 kW of power. However, today Stirling engines are limited to 25 kW. These are best matched with smaller dishes. Gas turbine heat engines based on micro-turbines can provide higher output but they are significantly less efficient that Stirling engines. Both micro-gas turbine and Stirling engine-based systems can be designed for hybrid operation using a combination of solar heat and the heat from combustion of natural gas [4].

As with both parabolic trough collectors and heliostats, solar dishes have to be able to track the sun across the sky in order to achieve maximum efficiency. Tracking systems tend to be expensive and this means that the cost of the dish plays a significant role in the economics of the power system. The dish support is usually constructed as a lattice upon which individual curved mirrors are mounted to create the overall dish. These mirrors may be of glass or polished metal, circular or rectilinear. At the centre of the dish there is a projecting beam to which the heat engine is attached, positioned so as to capture the heat concentrated at the focus of the dish. Dishes with Stirling engines have been built in sizes ranging from 5 kW to 25 kW. These engines are in theory capable of 40% energy conversion efficiency although practical engines today achieve closer to 30% [4].

2.4. Thermal storage

The molten salt system, used for thermal storage in solar thermal power plants, is typically a mixture of sodium and potassium nitrates which melts at about 220 °C [6]. In operation the salt is stored in a tank maintained at about 300 °C. Molten salt is taken from this tank and passed through the high temperature receiver where it absorbs heat provided by the mirrors from the collector field and is then returned to a high temperature storage tank at a temperature of around 550 °C. At this temperature the salt can act as a source of high-grade heat and it appears possible to operate with even higher temperatures if necessary [2].

Electricity is generated by taking molten salt from the hot storage tank and passing it through a heat exchanger where the heat it contains is transferred to water, generating steam to drive a steam turbine [6]. The cooled molten salt is then returned to the cold storage tank ready to pass through the solar energy receiver once more. By careful sizing of a plant of this type it is quite feasible to build a power station capable of providing power throughout the day and night.

3. Solar thermal power plants around the world

Solar thermal power technologies still need further research to overcome non-technical and technical barriers. Solar thermal power plants require a long-term view in the same way as traditional energy producing plants, and therefore benefit from stable policies and continuity of legal and financial frameworks, ideally favorable for solar thermal power systems. Additionally, with little commercial experience to draw on, realistic costs estimates for solar thermal power plants are extremely difficult to make, however, it is expected that cost reduction will result from technical progress. In this section, the available solar thermal power plants in operation and under construction around the world are briefly presented [10].

3.1. Solar thermal power plants in operation

3.1.1. Solar electric generating system

Solar Electric Generating System (SEGS) is the largest solar energy generating facility in the world. It consists of nine solar power plants, located at Mohave Desert, in California, USA, with an annual solar potential of 2700 kWh/m^2. The plants have a total of 354 MW installed capacity, with a gross average output for all nine plants around 75 MW. In addition, the turbines can be utilized at night by burning natural gas. The combined solar field has a total parabolic reflecting mirror area of over 2 million m^2 and the nine SEGS plants cover a land area of more than 6,400,000 m^2. Lined up, the parabolic mirrors would extend to over 369 km. The SEGS installation uses parabolic trough technology along with natural gas to generate electricity. Around 90% of the electricity is produced by the sunlight. Natural gas is only used when the solar power is insufficient to meet the electricity demand of southern California. The installation uses synthetic oil as heat transfer fluid which heats to over 400 °C, transferring its heat to generate steam from water, in order to drive the Rankine cycle steam turbine thereby generating electricity.

3.1.2. Nevada Solar One

Nevada Solar One is a solar thermal plant, based on the parabolic trough technology and is located in the El Dorado Valley in Nevada, USA. The solar field is made up of 760 solar parabolic trough collectors, each with a reflective surface of 470 m^2, to make up a total of 357,200 m^2 of solar reflective field, over a total land area of 1,600,000 m^2. The steam turbine has a nominal generating capacity of 64 MW and the plant produces annually around 130 GWh (annual capacity factor of 23%), while employing a supplementary gas heater facility for back-up steam generation in case solar irradiation is not adequate.

3.1.3. PS10

PS10 is an operational solar thermal plant based on the solar tower technology. It is located in Sanlucar de Mayor in Sevilla, Spain and begun operation in 2007. The plant has a land area of 600,000 m^2 and it is the first solar tower plant to begin commercial electricity generation operations in the world. The plant solar tower is 100 m high, and the heliostats that track the sun on two axes, and concentrate the sun's irradiation to the focal point (receiver) located on the tower, are 624 in total with a surface area of 120 m^2 each. Therefore, the total reflective surface area is 75,000 m^2. Each heliostat has an independent solar tracking

mechanism that directs solar radiation toward the receiver. The actual heliostat field does not however completely surround the receiver tower. In the northern hemisphere, the heliostat field is located on the north side of the tower to optimize the amount of solar radiation collected while minimizing heat loss. The receiver is located in the upper section of the tower. It is a "cavity" receiver and is comprised of four vertical panels that are 5.5 m wide and 12 m tall. The panels are arranged in a semi-cylindrical configuration and housed in a square opening 11 m per each side.

With an annual solar potential of 2100 kWh/m^2, and installed capacity of 11 MW, the plant is capable of generating 24.3 GWh of electricity annually (annual capacity factor of 25%). PS10 plant is capable of storing 1 h worth of steam for electricity generation via steam storage tanks. Steam is stored at 50 bar and 285 °C, and it condenses and flashes back to steam, when the pressure is lowered. Additionally, under low solar irradiation conditions, the plant is capable of supplying 12–15% of its capacity via natural gas combustion. The total plant efficiency, (conversion of solar irradiation to electricity) is approximately 17%. This is a fairly high number considering that the efficiency of the steam cycle alone is approximately 27%.

3.1.4. Andasol 1 and 2

Andasol 1 and 2 are two identical solar thermal plants expected to begin operations very soon and will then be the first solar thermal parabolic trough power plants to operate in Europe. These two 50 MW plants are located in Andalucia, Spain.

The Andasol 1 solar thermal plant consists of three basic parts: the solar field, the storage tanks and the power generation block. The solar field of each of the Andasol plant uses 624 parabolic mirrors arranged in 156 loops with a total reflective area of more than 510,120 m^2 in a land area of 2,000,000 m^2. Andasol 1 is estimated to supply annual electricity generation of 179 GWh. With an annual solar potential of 2201 kWh/m^2, total solar field annual average efficiency (efficiency of solar irradiance conversion to solar steam) is estimated around 43%, while the steam cycle efficiency is estimated to be 38.1%. Overall plant efficiency is thus around 16%.

The Andasol plants are the first solar thermal plants to utilize two molten salt storage tanks for heat storage in cases of low solar irradiation. Heat storage begins to occur at midday, when the sun irradiation is very high and electricity can be generated while, at the same time, the heat storage system can be charged. In order to charge the storage system, heat from the heat transfer fluid is transferred to the molten salt tank which collects the heat while the molten salt moves from the cold tank to the hot tank, where it accumulates until it is completely full. When heat is to be discharged, the salt cools down and moves to the cold tank. Since the cold and hot salts are kept in two separate tanks, this is called a two-tank system. The molten salt storage tank system increases the annual equivalent full-load running time of the solar thermal plant to around 3500 h. The two storage tanks have a diameter of 36 m and a height of 14 m each and have a storage capacity of 7.5 h at 50 MW. The quantity of the molten salts employed is estimated to be 28,500 t, with a melting temperature of 221 °C and allowed operational temperature range between 291 °C (cold tank) and 384 °C (hot tank).

3.2. Solar thermal power plants under construction

3.2.1. Solnova 1

Solnova 1 is a solar thermal plant to be manufactured in the Sanlucar de Mayor location in Seville, Spain, and it is based on the parabolic trough technology. The plant will use synthetic oil to generate high temperature steam and run a conventional steam cycle. The plant will be comprised of 90 rows of collectors oriented north–south. Every row will have four trough modules (therefore a total of 360 modules) that are each 12.5 m long and 5.76 m wide. Each module will rotate about its axis to track the sun. Enough space will be left between the rows to reduce losses due to shading and allow for easy operation and maintenance. The total reflective surface will be composed of approximately 260,000 m^2 of mirrors. The total land area required for the Solnova 1 plant will be around 1,200,000 m^2.

Solnova 1 installed capacity will be 50 MW and will be capable of generating 114.6 GWh of clean electrical energy annually (annual average capacity factor of 26%). In low solar irradiation conditions, the plant will be capable of supplying 12–15% of its capacity through natural gas combustion. At peak conditions, the plant will convert solar radiation into heat at efficiency near 57%. Combine with the efficiency of 34% of the steam cycle, the overall plant efficiency is estimated to be approximately 19%.

3.2.2. PS20

PS20 is a solar thermal tower plant under construction, with a similar technology to PS10. It is constructed next to the PS10 plant but with twice the capacity, that is 20 MW. PS20 will have 1255 sun-tracking heliostats each with a surface area of 120 m^2 and a solar tower 160 m long. It is expected to be able to generate 48.6 GWh per year, with a total land requirement of 900,000 m^2. PS20 will also have the possibility to burn natural gas to cover 12–15% of its capacity in case of low solar irradiation.

3.2.3. Solar Tres

Solar Tres solar thermal plant is being constructed in Andalucia, Spain. It is a solar tower based solar thermal plant with a capacity of 19 MW. Solar Tres will employ 2480 heliostats of a total reflective surface area of approximately 300,000 m^2 (120 m^2 surface area per heliostat), located in a land area of 1,420,000 m^2. Annual solar potential levels reach 2060 kWh/m^2. A unique feature of the Solar Tres plant is the use of molten salt as a heat transfer medium in the interior of the receiver, instead of the heat transfer fluid (synthetic oil) normally used in solar thermal power plants. This allows for the collection, transport and storage of the thermal energy with very high efficiencies through the high differential temperatures. Also, the molten salt flow loop reduces the number of valves, eliminates "dead legs" and allows fail-safe draining that keeps salt from freezing. Compared to the Andasol plants, Solar Tres will store three times more energy per kg of salt. The concentration of the sunlight on the receiver, situated on the top of a 120 m high tower, will produce temperatures of over 850 °C and the salt will be heated to approximately 565 °C. The salt then flows in molten state through a heat exchanger in which sufficient steam will be produced to operate the steam turbine of the power block. Annual electricity generation is expected to be 96.4 GWh, and overall plant efficiency around 14%.

Solar Tres plant will employ a large thermal storage system by using 6250 t of salt with insulated storage tank immersion heaters. This high capacity liquid nitrate salt storage system is efficient and low-risk and is designed for a high-temperature liquid salt at 565 °C (with a daily temperature drop of only 1–2 °C) and a cold temperature salt at 45 °C above its melting point (240 °C). The storage system may provide back-up steam for up to an additional 15 h. Solar Tres design will also employ a 43 MW steam generator system that will have a forced recirculation steam drum. This innovative design places components in the receiver tower structure at a height above the salt storage tanks that allows the molten salt system to drain back into the tanks, providing a passive fail-safe design. This will improve plant availability and reduced operation and maintenance costs.

Table 1
Indicative land area requirements for solar thermal power plants.

Solar thermal power plant	Capacity (MW)	Thermal storage (h)	Land area (m^2)	Specific land area (m^2/kW)
Parabolic trough technology				
SEGS	354	–	6,400,000	18
Nevada Solar One	64	–	1,600,000	25
Andasol	50	7.5	2,000,000	40
Solnova	50	–	1,200,000	24
Solar tower technology				
PS10	11	1	600,000	55
PS20	20	–	900,000	45
Solar Tres	19	15	1,420,000	75

3.2.4. Ibersol 1

The Ibersol 1 plant will be situated in Puertollano, Spain and will have a capacity of 50 MW, based on a parabolic trough technology. There will be 576 parabolic trough collectors arranged in 216 loops of four collectors per loop. Steam generation will be achieved via the use of a heat transfer fluid (thermal oil) and a thermal storage stage will also be constructed, based on the technology of molten nitrate salt tanks.

3.3. Overall comparison

The primary consideration for a solar thermal power plant is the amount of land needed, which is significant. The land area requirements depend on the available area solar potential as well as on the degree of the integrated thermal storage. Also, with little commercial experience to draw on, realistic land estimates for solar thermal power plants are extremely difficult to make. The land area requirements of the various existing solar thermal power plants are tabulated in Table 1. Parabolic troughs require a land area of approximately 25 m^2/kW, in the case where no thermal storage is integrated. Solar towers have the highest requirement of approximately 45 m^2/kW, in the case where no thermal storage is integrated.

4. Cyprus current energy system

Cyprus has no indigenous hydrocarbon energy sources and energy-wise is almost completely dependent on imported fossil fuels. Currently, solar energy is used solely for water heating in the domestic and tourist sector. It has been estimated that about 90% of individual homes, 80% of apartments and 50% of hotels are equipped with solar-water heating systems, making Cyprus the first country in the world with installed solar collectors per inhabitant [9]. In particular, for 2006, about 690,000 m^2 of solar water heating collectors were installed in Cyprus with an installed solar water heating collector area per inhabitant around 1 m^2/inhab.

For many decades the power industry in Cyprus developed on the basis of available technology and know-how, and today it constitutes a key sector of the economy. Until 2004 the Electricity Authority of Cyprus (EAC) was responsible for the generation, transmission and distribution of electricity in Cyprus [12]. This situation, however, changed and the electricity market in Cyprus is now open. A Regulator's Office and a Transmission System Operator have been appointed and new participants are expected to join the electricity sector in the future. However, at the moment, EAC is still the sole producer of electricity on the island and operates three thermal power stations with a total installed capacity of approximately 1.2 GW [8]. Future plans involve the installation of combined cycle technologies on the island using diesel as fuel in the first case and at a later stage natural gas when available to the island. The first combined cycle unit with capacity of 220 MW is expected to be in operation after the year 2009, while two more combined cycle units of the same capacity are expected to be in operation after the year 2012.

Cyprus power system operates in isolation and for electricity production relies totally on imported fuels such as, heavy fuel oil and diesel with a share of 98% and 2% respectively. Cyprus economic growth in the past 30 years average 5.8% per year and 3.1% per year over the last 10 years. In order to support the economic growth experienced in Cyprus the electricity consumption has risen from 2181 GWh in 1995 to 4786 GWh in 2007. This is translated by an 89.6% increase, averaging to 8.1% per year. The average price of electricity for the year 2007 was approximately 0.13 €/kWh.

The penetration of RES for power generation technologies in Cyprus is currently negligible. It amounts to a few cases of small PV systems installed in homes, and to a smaller degree, biomass gasification (using wood, agricultural wastes, olive kernels, almond husks, etc.). Despite the almost zero penetration of RES for power generation technologies in Cyprus, a large amount of licenses have recently been granted by Cyprus Energy Regulatory Authority pertaining to electricity generation from wind parks. The wind park installations that have been so far approved account for a total generation of approximately 840 MW, while there are still pending applications for approval for another 246 MW of wind energy.

In view of the new European Union (EU) energy policy for climate change [3] setting RES targets for year 2020 Cyprus' commitment to the EU to have a contribution by renewable energy resources will be 13% of the total energy consumed by 2020. A series of measures and incentives are currently being discussed that are expected to be announced in the near future. Briefly, solar thermal power plants are eligible for feed-in tariff with a ceiling of 25 MW by the year 2015. The purchase contract period is 20 years and the relevant feed-in tariff is 0.26 €/kWh.

5. Parametric cost–benefit analysis

The main objective of this feasibility study is to investigate whether the installation of parabolic trough solar thermal technology for power generation in the Mediterranean region is economically feasible. The case study takes into account the available solar potential for Cyprus, as well as all available data concerning current RES policy of the Cyprus Government, including the relevant feed-in tariff of 0.26 €/kWh. In order to identify the least cost feasible option for the installation of the parabolic trough solar thermal plant a parametric cost–benefit analysis is carried out by varying the following parameters: (a) parabolic trough solar thermal plant capacity 25 MW or 50 MW or 100 MW, (b) parabolic trough solar thermal capital investment from 2000 €/kW to 8000 €/kW, (c) operating hours from 5 h/day to 24 h/day, (d) required land leasing from 0 €/m^2 to 3 €/m^2 and (e) CO_2 ETS price 0 €/t_{CO2} or 30 €/t_{CO2}. For all above cases the electricity unit cost or benefit before tax (in €/kWh), as well as after tax cash flow, net present value (NPV), internal rate of return (IRR) and payback period are calculated.

5.1. Cyprus solar potential

Cyprus lies in a sunny belt with an average yearly solar potential on a flat surface to be around 1790 kWh/m^2. During the months of March and September there is a considerable high sunlight radiation. This provides the fundamental grounds for the adoption of parabolic trough solar thermal technology for generating electricity. Different statistical analyses have shown that all parts of Cyprus enjoy sunny climate. The island is exposed to sunlight radiation on average 9.8 h in December and 14.5 h in June.

In particular, solar thermal power generation views the sun as a source of heat which can be utilized by concentration. More specifically, sunlight consists by 46% of infrared radiation or heat energy. This is easily absorbed by many materials which, when exposed to sunlight, become hot. Some visible light will also be absorbed and this may be degraded into energy too. However, much visible light is reflected. For Cyprus conditions, in the case of using parabolic trough solar thermal technology for power generation the annual solar potential is estimated between 1950 kWh/m^2 and 2050 kWh/m^2.

5.2. Input data and assumptions

The input data and assumptions used for the above analysis are tabulated in Table 2. For the purpose of this parametric study we assume the installation and operation of a parabolic trough solar thermal plant with a capacity of either 25 MW or 50 MW or 100 MW. The parabolic trough solar thermal collector system is assumed to receive an annual solar potential of 2000 kWh/m^2 with a typical solar to electricity efficiency of 15%. In addition, in order to cover various losses, such as transformer losses, etc., a typical value of 14% is assumed.

The effect of thermal storage is examined in this parametric analysis by varying the operating hours of the solar thermal plant from 5 h/day, in steps of 5 h/day, up to 24 h/day. For the purposes of this study one operating hour refers to the corresponding hourly maximum electricity production from the solar thermal plant, i.e., for 25 MW capacity plant the electricity generation for 1 h will be 25 MWh). Thus, in the case of Cyprus a parabolic trough solar thermal power plant can approximately operate with no thermal storage for 5 h/day. For daily operating hours greater than 5 h thermal storage is necessary with a direct effect on (a) capital cost (greater solar field is necessary), (b) land area (greater area to accommodate resulting solar field size is necessary) and (c) electricity production (power production is increased due to increased operating hours).

Parabolic trough solar thermal plants for power generation applications are not currently cost-competitive due to the high initial cost. Thus the effect of the capital cost is examined in this parametric analysis by varying the initial expenditure from 2000 €/kW, in steps of 1000 €/kW, up to 8000 €/kW. The capital expenditure may include, among others, the following costs: feasibility study, land leasing, solar thermal collector system, power block system, development and design study, license fees, engineering works, road construction, connection transmission line, substation, commissioning and training, contingencies, etc.

To estimate the greenhouse gas emission reduction (mitigation) potential of the parabolic trough solar thermal power plant, the CO_2 environmental indicator which currently characterizes Cyprus power system of 800 g/kWh is used. In order to take into account the EU ETS system as well as the emerging rules from the Kyoto Protocol, associated with CDM (clean development mechanisms) and JI (joint implementation) projects, CO_2 ETS prices of 0 €/t_{CO2} and 30 €/t_{CO2} are used. By doing this the number of CO_2 credits that accrue to the parabolic trough solar thermal power plant can be determined and their benefit to the cash flow can be calculated.

For the operation cost, a fixed annual expenditure of €4,000,000 is taken into account for staff salary and overheads (such as insurance charges, etc.). Annual maintenance expenditure is assumed as 1% of the total investment cost. The effect of land cost is examined in this parametric analysis by varying land leasing cost from 0 €/(m^2 year), in steps of 0.5 €/(m^2 year), up to 3 €/(m^2 year). Also, the economic life of the plant is assumed at 20 years with a fixed feed-in tariff of 0.26 €/kWh. Throughout the simulations, a typical discount rate of 6% is assumed. In order to calculate the after-tax cash flows and after-tax financial indicators a single 10% income tax rate is assumed that is constant throughout the project life and applied to net income.

Table 2
Parametric cost–benefit analysis data and assumptions.

Parameter	Value
Technical data	
Plant capacity	25 MW or 50 MW or 100 MW
Annual solar potential	2000 kWh/m^2
Solar thermal collector system	Parabolic trough
Operating hours	5–24 h/day
Solar to electricity efficiency	15%
Losses	14%
Capital data	
Specific capital cost	2000–8000€/kW
Emissions data	
CO_2 indicator	800 g/kWh
CO_2 ETS price	0 €/t_{CO2} or 30 €/t_{CO2}
Operation and maintenance data	
Annual staff and overheads cost	4,000,000 €/year
Annual maintenance cost	1% of capital cost
Annual land leasing	0–3 €/(m^2 year)
Other data	
Discount rate	6%
Available feed-in tariff	0.26 €/kWh
Economic life of solar thermal plant	20 years
Annual income tax rate	10%

5.3. Simulation procedure

In order to identify the least cost feasible options for the installation of a parabolic trough solar thermal plant based on the current market regulations (i.e., 20 years purchase contract and a feed-in tariff of 0.26 €/kWh) 1470 simulations have been carried out based on the data and assumptions discussed in the previous section. For all simulations, the IPP algorithm version 2.1 (independent power producer technology selection algorithm) software tool is employed [7].

The software, allows the user to input various technical, financial and environmental parameters of a parabolic trough solar thermal power plant, such as efficiencies, solar potential, discount rates, etc. Then, the operation of the plant is simulated and the key financial feasibility indicators, such as IRR, payback period, NPV, etc., are calculated based on the following algorithm: (a) calculate solar radiation in plane of parabolic trough solar field, (b) calculate electrical energy delivered by solar thermal plant, (c) calculate system losses, (d) calculate electrical energy delivered to the grid, (e) calculate required area for parabolic trough solar field, (f) calculate required area for the installation of the solar thermal power plant, (g) calculate feed-in tariff benefit, (h) calculate CO_2 emissions avoided benefit, (i) calculate financial feasibility indicators, assuming that the initial investment year is year 0, the costs and credits are given in year 0 terms, thus any inflation rate (or the escalation rate) is applied from year 1 onwards and the timing of cash flows occurs at the end of the year.

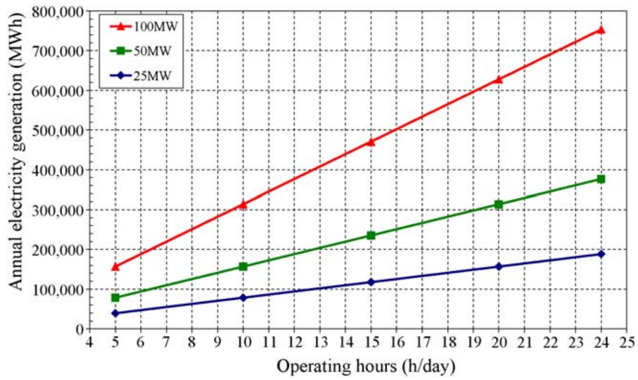

Fig. 4. Results for annual electricity generation from various solar thermal plant sizes and different operating hours.

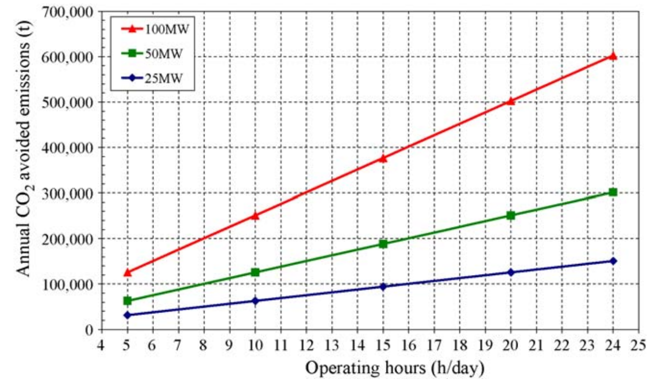

Fig. 6. Results for annual CO_2 avoided emissions from various solar thermal plant sizes and different operating hours.

During the simulations procedure the following financial feasibility indicators are calculated: (a) electricity unit cost or benefit before tax (in €/kWh), (b) after tax cash flow (in €), (c) after tax NPV (is the value of all future cash flows, discounted at the discount rate, in today's currency), (d) after tax IRR (is the discount rate that causes the NPV of the project to be zero and is calculated using the after tax cash flows. Note that the IRR is undefined in certain cases, notably if the project yields immediate positive cash flow in year 0), (e) after tax payback period (the number of years it takes for the cash flow, excluding debt payments, to equal the total investment which is equal to the sum of the debt and equity).

5.4. Results and discussion

The electricity production from a parabolic trough solar thermal power plant depends on the available solar potential as well as on the number of operating hours and the degree of thermal storage. The results obtained concerning the annual electricity generation from the three sizes of solar thermal plants examined for different operating hours are presented in Fig. 4. It is evident that as the size of the solar thermal plant increases and the number of daily operating hours increases (note that for daily operating hours greater than 5 h thermal storage is necessary) the electricity production increases as well.

The total land area required (including shading and other purposes spaces) for the installation of parabolic trough solar thermal plants of different capacities and operating hours is presented in Fig. 5. We observe that as the size of the solar thermal plant increases and the number of daily operating hours increases (note that for daily operating hours greater than 5 h thermal storage in necessary) the required land area increases as well. For example in the case of a solar thermal power plant with a capacity of 25 MW and operating hours of 5 h/day (no thermal storage) the required land area required is approximately 562,404 m^2 that is a square plot of approximately 750 m by 750 m. Also, in the case of a solar thermal power plant with a capacity of 100 MW and operating hours of 5 h/day (no thermal storage) the required land area required is approximately 2,249,616 m^2 that is a square plot of approximately 1500 m $\times$ 1500 m. In the case of a solar thermal power plant with a capacity of 100 MW and operating hours of 24 h/day (with thermal storage) the required land area required is approximately 10,798,160 m^2 that is a square plot of approximately 3286 m $\times$ 3286 m.

The results obtained concerning the annual avoided CO_2 emissions and the annual barrels of crude oil not consumed from the three sizes of solar thermal plants examined for different operating hours are illustrated in Figs. 6 and 7 respectively.

The results obtained concerning the electricity unit cost or benefit before tax, for different solar thermal plant sizes in the case of five operating hours per day without and with CO_2 trading, are illustrated in Figs. 8 and 9 respectively. Positive values of electricity unit cost indicate benefit (i.e., profit) whereas negative values indicate cost (i.e., loss). For example, referring to Fig. 8, concerning a 25 MW solar thermal power plant operating at 5 h/day (i.e., no thermal storage) and no trading of the avoided CO_2 emissions, in the case of capital cost of 2000 €/kW and land leasing price of 1.5 €/(m^2 year), the calculated electricity production cost is 24.73 €c/kWh. Thus, taking into account a feed-in tariff of 26 €c/kWh, before tax electricity unit benefit is 1.27€c/kWh (positive sign indicating benefit) meaning that for every kWh produced by the solar thermal power plant and delivered to the grid a profit (or benefit) before tax of 1.27 €c will occur. Whereas,

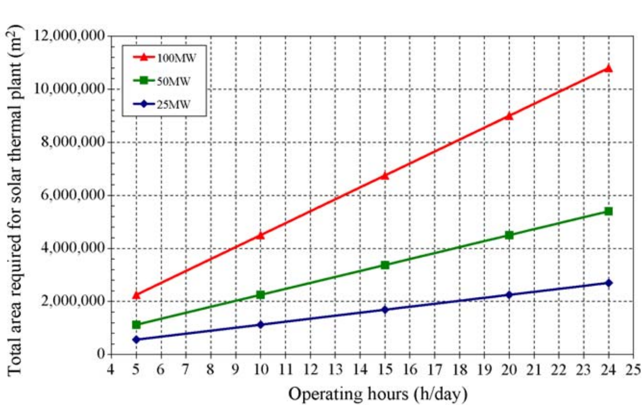

Fig. 5. Results for required area from various solar thermal plant sizes and different operating hours.

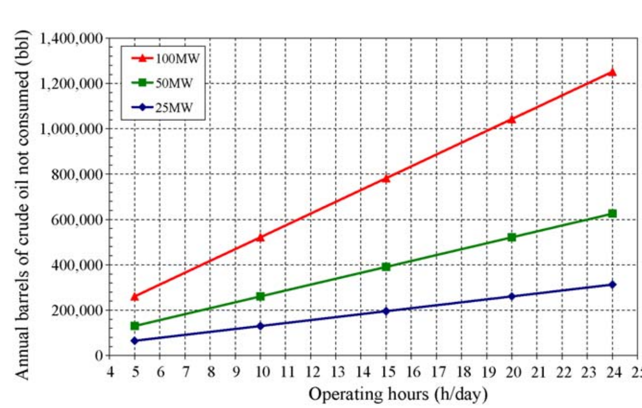

Fig. 7. Results for annual barrels of crude oil not consumed from various solar thermal plant sizes and different operating hours.

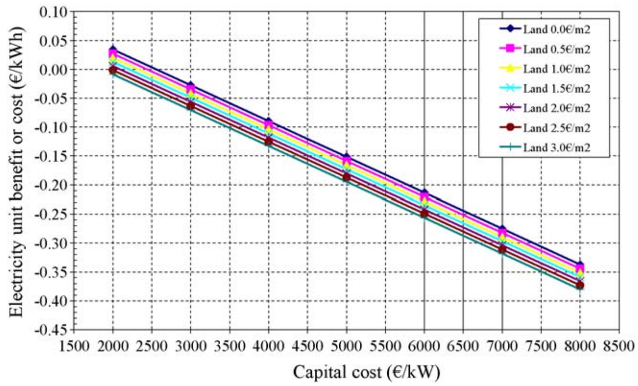

Fig. 8. Before tax electricity unit cost in the case of 25 MW solar thermal plant, operating hours 5 h/day and no CO_2 trading.

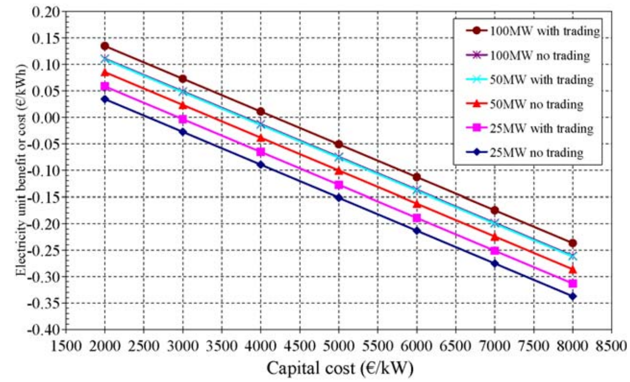

Fig. 10. Before tax electricity unit cost in the case of operating hours 5 h/day and no land leasing.

referring again to Fig. 8, in the case of capital cost of 4000 €/kW and land leasing price of 1.5 €/(m^2 year), the calculated electricity production cost is 36.40 €c/kWh. Thus, taking into account a feed-in tariff of 26 €c/kWh, before tax electricity unit cost is −10.40 €c/kWh (negative sign indicating cost) meaning that for every kWh produced by the solar thermal power plant and delivered to the grid a loss (or cost) before tax of 10.40 €c will occur.

The results concerning a 25 MW solar thermal power plant operating at 5 h/day (i.e., no thermal storage) in the case of trading the avoided CO_2 emissions at 30 €/t are illustrated in Fig. 9. For the case of capital cost of 2000 €/kW and land leasing price of 1.5 €/(m^2 year), the calculated electricity production cost is 24.73 €c/kWh. Thus, taking into account a feed-in tariff of 26 €c/kWh and the CO_2 emissions trading price of 30€/t, before tax electricity unit benefit 3.67€c/kWh (positive sign indicating benefit) meaning that for every kWh produced by the solar thermal power plant and delivered to the grid a profit (or benefit) before tax of 3.67 €c will occur. Whereas, referring again to Fig. 9, in the case of capital cost of 4000 €/kW and land leasing price of 1.5 €/(m^2 year), the calculated electricity production cost is 37.11 €c/kWh. Thus, taking into account a feed-in tariff of 26 €c/kWh and the CO_2 emissions trading price of 30€/t, before tax electricity unit cost is −8.71 €c/kWh (negative sign indicating cost) meaning that for every kWh produced by the solar thermal power plant and delivered to the grid a loss (or cost) before tax of 8.71 €c will occur.

The benefit of CO_2 trading on parabolic trough solar thermal plant electricity unit cost for various trading prices is illustrated in Fig. 15. Trading of the avoided CO_2 emissions ranging from 0.4 €c/kWh (for an ETS price of 5 €/t_{CO2}) to 3.6 €c/kWh (for an ETS price of 45 €/t_{CO2} appears to be an added value to the profitability of the parabolic trough solar thermal plant. For example the additional benefit due to CO_2 emissions trading price of 30 €/t for all cases examined during the simulations performed is calculated at 2.4 €c/kWh. Also based on the simulations, land leasing price affect negatively the final production cost by the relation: for every 1 €/(m^2 year) increase in land leasing price the final production electricity cost from the solar thermal power plant increases by 1.43 €c/kWh.

Finally, the size of the solar thermal plant is critical for the viability of the investment. From the simulations performed it is clear that by increasing the size of the parabolic trough solar thermal power plant (i.e., from 25 MW to 50 MW or 100 MW) the investment becomes more attractive. This is illustrated graphically in Figs. 10–14 for various degrees of operating hours.

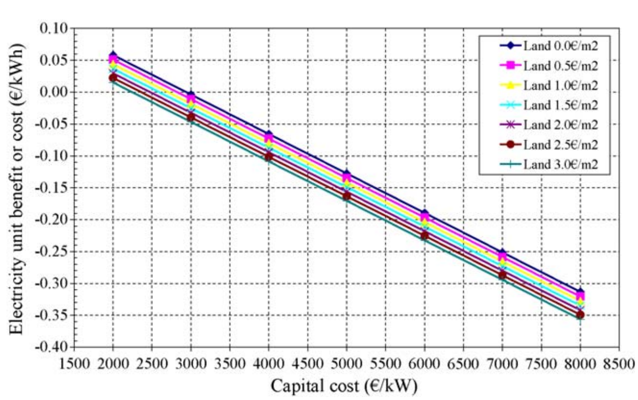

Fig. 9. Before tax electricity unit cost in the case of 25 MW solar thermal plant, operating hours 5 h/day and with CO_2 trading.

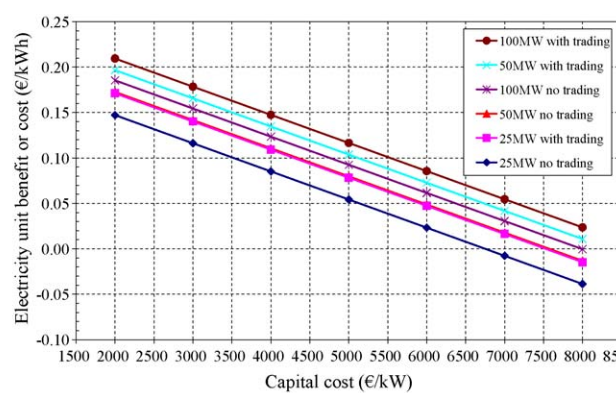

Fig. 11. Before tax electricity unit cost in the case of operating hours 10 h/day and no land leasing.

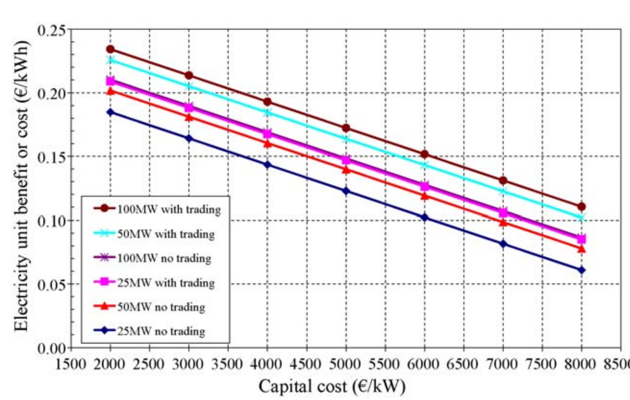

Fig. 12. Before tax electricity unit cost in the case of operating hours 15 h/day and no land leasing.

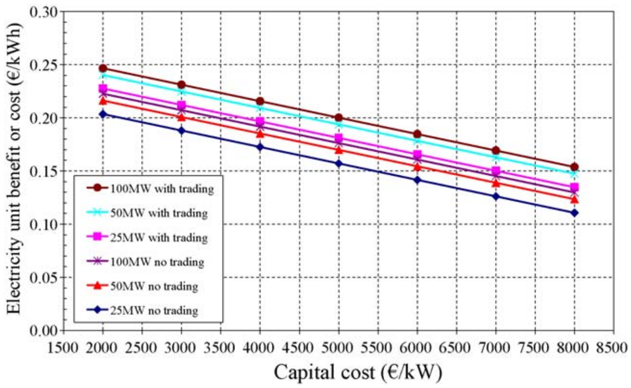

Fig. 13. Before tax electricity unit cost in the case of operating hours 20 h/day and no land leasing.

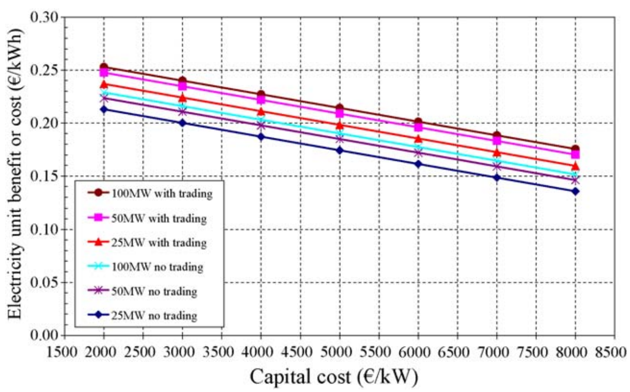

Fig. 14. Before tax electricity unit cost in the case of operating hours 24 h/day and no land leasing.

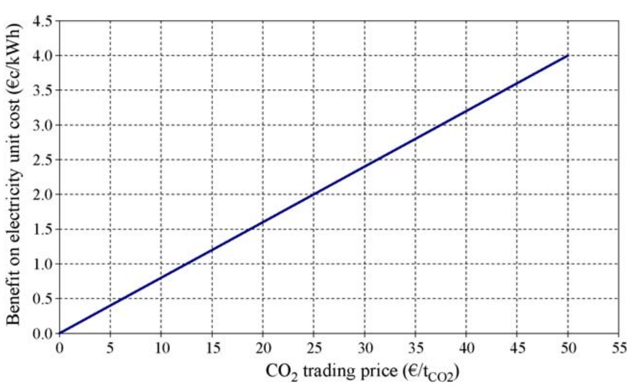

Fig. 15. Benefit of CO_2 trading on parabolic trough solar thermal plant electricity unit cost for various ETS prices.

The NPV and the payback period are directly related to the cash flow of the investment, thus, on the electricity unit benefit or cost. Therefore, the results obtained during the simulations concerning after tax NPV and payback period provide similar observations as those discussed before. It is obvious from the above analysis that (a) the size, (b) the capital expenditure and (c) the operating hours of the parabolic trough solar thermal power plant, are critical parameters for the viability of the project.

6. Conclusions

With little commercial experience to draw on, realistic costs estimates for solar thermal power plants are extremely difficult to make, however, it is expected that cost reduction will result from technical progress. Parabolic troughs require a land area of approximately 25 m^2/kW, in the case where no thermal storage is integrated. Solar towers have the highest requirement of approximately 45 m^2/kW, in the case where no thermal storage is integrated. Many solar thermal power projects are currently in the pipeline (mainly in Spain) including plants using storage and ISCC plants (mainly in Morocco, Algeria and Spain).

The main objective of this feasibility study was to investigate whether the installation of a parabolic trough solar thermal technology for power generation in the Mediterranean region is economically feasible. The study took into account the available solar potential for Cyprus, as well as all available data concerning current RES policy of the Cyprus Government including the relevant feed-in tariff of 0.26 €/kWh.

The results obtained concerning the annual electricity generation from the three sizes of solar thermal plants examined for different operating hours indicated that as the size of the solar thermal plant increases and the number of daily operating hours increases (note that for daily operating hours greater than 5 h thermal storage is necessary) the electricity production increases as well. The results obtained concerning total land area required (including shading and other purposes spaces) for the installation of parabolic trough solar thermal plants indicated that as the size of the solar thermal plant increases and the number of daily operating hours increases the required land area increases as well. Also, the results indicated that the additional benefit due to CO_2 emissions trading price of 30 €/t for all cases examined during the simulations performed is at 2.4 €c/kWh. The results indicated that land leasing price affect negatively the final production cost by the relation: for every 1 €/(m^2 year) increase in land leasing price the final production electricity cost from the solar thermal power plant increases by 1.43 €c/kWh. Finally, the results indicated that the size of the solar thermal plant is critical for the viability of the investment. From the simulations performed it is clear that by increasing the size of the parabolic trough solar thermal power plant (i.e., from 25 MW to 50 MW or 100 MW) the investment becomes more attractive.

Based on this work, the overall results indicate that the installation of a parabolic trough solar thermal technology for power generation in the Mediterranean region (such as in the case of the island of Cyprus) can be profitable and economically feasible under certain conditions. These conditions depend mainly on the size of the plant, the degree of storage, the initial cost and the cost of land.

Acknowledgement

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